Angular-Momentum Transfer in Deeply Inelastic Scattering of 610-MeV ^{86}Kr by ^{209}Bi

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For the reaction 610-MeV $^{86}Kr + ^{209}Bi$, angular correlations of fragments from fissioning heavy reaction products have been measured with respect to the recoil direction, both in and out of the reaction plane. The deduced angular momentum of the recoil particle is large, $(50-70)\hbar$, and is consistent with that of the sticking limit and greater than that of the rolling limit. This result demonstrates the importance of the tangential component of the frictional force.

In reactions between high-energy, very heavy ions, the deeply inelastic scattering process is characterized by strong damping of the initial kinetic energy, angular distributions peaked near the grazing angle, and average charge and mass characteristic of the target and projectile. In the case of 610-MeV $^{86}Kr + ^{209}Bi$, the reaction cross section is dominated by this process[1]; the combined Coulomb and nuclear potentials give rise to a focusing of most partial waves into an angle near the grazing angle.[2]

Much of the effort to understand this reaction mechanism has been devoted to solving the classical equations of motion, with the introduction of phenomenological viscous friction forces to describe the dissipation of initial kinetic energy and angular momentum into internal degrees of freedom.[3-5] The frictional forces are usually decomposed into radial and tangential components. Only the tangential component gives rise to a transfer of the initial orbital angular momentum into the intrinsic angular momentum of the fragments.

This paper reports one of the first measurements of the angular momentum deposition in a deeply inelastic reaction induced by a heavy ($A > 20$) projectile. We determine the amount of angular momentum transferred from the initial orbital angular momentum to the intrinsic spin of the heavy reaction product (the recoil) by measuring angular correlations of fission fragments from this heavy product relative to the recoil axis.[6] Measurements of γ-ray multiplicities are also in progress,[7] from which angular-momentum transfers may be deduced with assumptions about the relation between multiplicity and fragment angular momenta. Our results show that the angular-momentum transfer is very large, and suggest that tangential friction is stronger than has often been assumed.

The geometry of the experiment is shown in Fig. 1. Fission fragments are measured in coincidence with the projectilelike reaction products. We designate the plane defined by the beam and the detected projectilelike particle as the reaction plane. Correlations in and out of the reaction plane were measured. A 610-MeV ^{86}Kr beam of intensity 40 $e\cdot$nA from the Lawrence Berkeley Laboratory Super-HILAC was incident on a target consisting of 300-$\mu g/cm^2$ ^{209}Bi evaporated onto a 50-$\mu g/cm^2$ carbon foil. Light (Kr-like) products were detected and identified by a $\Delta E \times E$ semiconductor counter telescope fixed at 40° laboratory angle, where the deeply inelastic scattering cross section is at a maximum. The measured angle and energy of the light product were used to determine the direction of the recoil, which is required for interpretation of the angular correlations. Two single surface-barrier counters for detection of fission fragments were mounted 50° apart on a separate rotating table in the scattering chamber. The more forward of these two detectors was mounted on an arm that could be moved to various out-of-plane angles. The more backward detector remained in the reaction plane. An event was defined by a coincidence between a light product detected in the

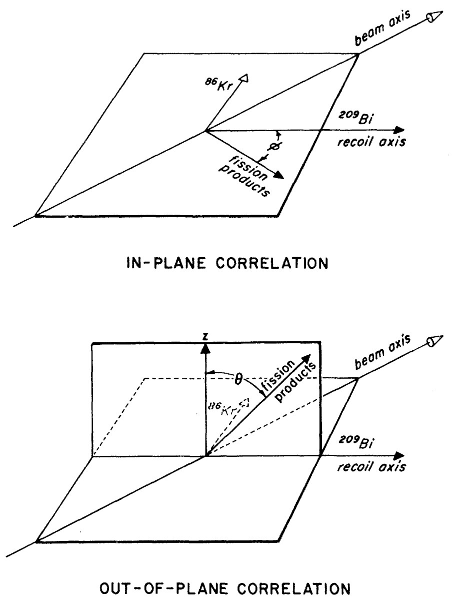

FIG. 1. Geometry of the experiment. The ^{86}Kr and ^{209}Bi labels designate projectilelike and targetlike products.

telescope and a fission fragment detected in one of the two single counters. In a two-dimensional array of counts versus telescope energy and fission-fragment energy (after a subtraction of random events) the events of interest were easily separable from other events. In this paper we present the angular correlations obtained after summing over all Z's and all light-product energies. (A later paper will report correlations for varying Z and Q value.)

The angular distribution, with respect to a space-fixed z axis, of fission fragments from a nucleus having quantum numbers J, M, and K is given by

$$W_{MK}^{J}(\theta) = \tfrac{1}{2}(2J+1)\,|d_{MK}^{J}(\theta)|^2,$$

where J is the intrinsic angular momentum of the fissioning nucleus, M is the projection of J on the z axis, K is the projection of J on the nuclear symmetry axis, θ is the angle measured from the z axis, and the $d_{MK}^{J}(\theta)$ are rotational wave functions.

In order to calculate a family of angular correlation curves that can be compared to experimental data, it is necessary to sum the above distribution over J, M, and K with the appropriate weighting functions. The K distribution depends only on the properties of the fissioning nucleus, and is taken from previous experiments. The J and M distributions depend on the reaction mechanism; these are to be determined from the experiment. The out-of-plane correlation is more sensitive to the J distribution; the in-plane, to the M distribution. In the limit of $M=J$ (that of equatorial collisions in the classical limit) the in-plane correlation is isotropic and the out-of-plane correlation is anisotropic, with the anisotropy increasing with increasing J.

A Gaussian distribution of K values is assumed. The parameter characterizing the width of the distribution, K_0^2, is taken from the extrapolation of previous low-energy measurements[8-10] of K_0^2 for the compound nucleus $^{213}_{85}$At as a function of excitation energy guided by the result of Clark *et al.*[11] at a high energy. The Z distributions of the coincident projectilelike particles indicate that the most probable Z of the heavy fragment is between $Z=84$ and $Z=85$ and that more than three-fourths of the events have Z values within a range of six Z units. K_0^2 varies by less than 22% over this Z range and the use of an average value should introduce only a small error.

We assume that the excitation energy associated with the average observed energy loss in the collision is divided according to the mass ratio of the two reaction partners.[12] The earlier measurements of fission-fragment anisotropies provide a calibration of the relationship between anisotropy and J in the present analysis, so that no further assumptions about the properties of the fissioning nucleus are required. This procedure automatically takes care of such effects as the removal of angular momentum by neutron evaporation prior to fission.

For the J distribution we take $P(J) \propto (2J+1)$ up to some maximum $J_{\max}$, where there is a sharp cutoff. This form follows from a model in which all partial waves up to some maximum l give rise to particles scattered to about 40° laboratory angle, and in which the fraction of orbital angular momentum transferred into intrinsic angular momentum is the same for all partial waves. The first of these assumptions is supported by the sharply peaked differential cross section which accounts for most of the reaction cross section. The second holds in either the rolling or sticking limits discussed later. A complete dynamical calculation with dissipative forces will be necessary to give a more accurate shape for the J distribution.

The measured in-plane and out-of-plane fission correlations are shown in Fig. 2. Laboratory angles and cross sections have been converted to

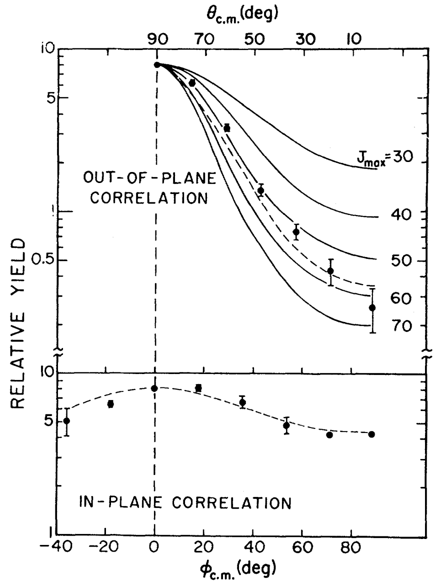

FIG. 2. Fission angular correlations measured in and out of the reaction plane. The family of solid curves are calculated for the out-of-plane case with $M=J$, $K_0^2=132$. The dashed curve is with $J_{min}=18$, $J_{max}=58$, and with contribution from $M \neq J$ (see text).

those of the ^{209}Bi center-of-mass coordinate system. Also shown for the out-of-plane case are a family of curves calculated for $K_0^2=132$, $M=J$, and varying J_{max}. The large out-of-plane anisotropy is a direct indication of sizable angular-momentum transfer with the resulting intrinsic angular momentum being predominantly oriented perpendicular to the reaction plane. Comparison of the anisotropy with the model calculations just described lead to an initial estimate of the transferred angular momentum of 55$\hbar$.

The anisotropy in the in-plane correlation could arise either from a contribution due to instantaneous fission or from interactions that lead to angular-momentum vectors whose projections in the reaction plane are not isotropically distributed. The calculations of Deubler and Dietrich[13] indicate that instantaneous fission should be negligible for a target with a high-fission barrier such as Bi. Nonequatorial collisions can give rise to a component of angular momentum that is not perpendicular to the reaction plane but is nearly perpendicular to the recoil direction. A previous study[14] of in-plane and out-of-plane fission-fragment angular correlations for another Coulomb-dominated direct reaction (albeit with a much lighter projectile) suggests that under the conditions of this experiment the angular-momentum vectors will be aligned predominantly perpendicular to the reaction plane.

If the in-plane anisotropy is due to nonequatorial collisions, a comparison of the out-of-plane correlation data to the family of curves in Fig. 2 results in an underestimate of the angular-momentum transfer. Estimates of this effect indicate that J_{max} increases 15 to 20 units when the in-plane and out-of-plane data are fitted simultaneously. Another effect that must be considered is that partial waves of small l may not contribute to the deeply inelastic cross section. Upper limits on the fusion cross section give upper limits to the l values that contribute to fusion. Such an effect could lower our estimate of angular-momentum transfer by 10 to 15 units. The dashed curves in Fig. 2 are fom a preliminary calculation taking these factors into account, with $J_{max}=58$ and $J_{min}=18$. The angular-momentum vectors were assumed to lie in the plane perpendicular to the recoil axis with a Gaussian ($\sigma=27°$) distribution of angles with respect to the z axis.

We thus conclude that the maximum angular momentum transferred is between (50 and 70)$\hbar$. Simple macroscopic models[4,5] suggest that there should be strong sliding friction that would lead to a rolling motion and that rolling friction could lead to sticking. In the sticking limit for spheres in contact, the fraction of angular momentum transferred to the heavy product for the ^{86}Kr + ^{209}Bi reaction is 0.29. (We neglect in this discussion deformation effects in the exit channel which will lower this fraction somewhat.) For the rolling limit this ratio is 0.16. Since partial waves of large l give rise to recoils of low excitation energy, which do not often fission, the effective l_{max} is smaller than that of the grazing trajectory. By considering the observed fission probability as a function of light-product energy loss, we select $l_{max}=235$, slightly lower than the grazing angular momentum of 270. J_{max} is thus 68 for the sticking limit and 39 for the rolling limit. The observed angular-momentum deposition in the heavy fragment is higher than the value of 39$\hbar$ expected in the rolling limit and somewhat less than but consistent with the 68$\hbar$ expected in the sticking limit of spheres in contact. It implies that the tangential friction component is very important. The only calculation that has been performed for this particular system and bombarding energy is a friction model calculation of Gross, Kalinowski, and De.[3] They obtain a total loss (that going into both fragments) of orbital angular momentum of 38$\hbar$. This corresponds to a somewhat smaller fraction of the initial angular momentum than that obtained in the present experiment. Thus this calculation, which has a tangential component much weaker than the radial component, underestimates the tangential component. If the dissipative forces are due to one-body viscous forces, one expects a tangential component that is one half that of the radial component.[15]

This determination of the angular-momentum deposition provides a crucial piece of information against which future theoretical calculations must be tested.

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n-d Breakup Calculations with the Reid Interaction

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The neutron-deuteron breakup amplitude is obtained for the Reid soft-core potential by solving the Faddeev equations exactly for the s-wave parts of the two-nucleon T matrix while the higher-partial-wave components of the force are treated perturbatively. Results are presented at 22.7 and 46.3 MeV. In particular it is found that the very deep minima in some breakup cross sections calculated with pure s-wave potentials are filled in predominantly by the p-wave components of the force.

In the majority of studies on neutron-deuteron scattering use has been made of pure s-wave potentials of either a separable or a local form. Calculations with more realisitic two-nucleon interactions have been restricted mainly to elastic scattering.[1-4] With respect to the breakup process it is only quite recently that results have been presented for separable interactions including the tensor force and p waves.[5] In this Letter we report on a calculation of the n-d breakup reaction using the full Reid soft-core interaction.[6]

In determining the transition matrix elements for the breakup reaction, use was made of the same approximation as in the case of elastic scattering, i.e., the non-s-wave components of the two-nucleon force are treated perturbatively in first order only. Also in this case the perturbation contains the s-d and d-d matrix elements of the $^3S_1$-$^3D_1$ channel, the $^1D_2$, $^3D_2$, $^3P_0$, $^3P_1$, and $^1P_1$ channels, and the p-p matrix elements of the $^3P_2$-$^3F_2$ channel of the two-nucleon T matrix. As a byproduct also the matrix elements for the elastic scattering can be obtained from the breakup amplitude by direct integration. These serve